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Possible detection of relic neutrinos and determination of their mass: quantitative analysis*

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We consider the possibility that a large fraction of the ultrahigh energy cosmic rays (UHECRs) are decay products of Z bosons which were produced in the scattering of ultrahigh energy cosmic neutrinos (UHECνs) on cosmological relic neutrinos (Rνs). We compare the observed UHECR spectrum with the one predicted in the above Z-burst scenario and determine the mass of the heaviest Rν as well as the necessary UHECν flux via a maximum likelihood analysis.

I. INTRODUCTION

Big-bang cosmology predicts the existence of the cosmic microwave background radiation (CMBR) and a similar background of Rνs with an average number density of $\langle n_{\nu_i}\rangle \approx 56$ cm^{-3} per light neutrino species i ($m_{\nu_i} < 1$ MeV). However, the Rνs have not been detected until now.

A possibility for their detection was discussed some time ago: the UHECν spectrum should have absorption dips at energies $\approx E_{\nu_i}^{\rm res} = M_Z^2/(2\,m_{\nu_i}) = 4.2\cdot 10^{21}$ eV (1 eV/m_{ν_i}) due to resonant annihilation with the Rνs into Z bosons of mass M_Z [1–3]. Recently it was realized that the same annihilation mechanism might already be visible in the UHECR spectrum [4,5] at energies above the predicted Greisen-Zatsepin-Kuzmin (GZK) cutoff [6–8] around $4\cdot 10^{19}$ eV. It was argued that the UHECRs above the GZK cutoff are mainly protons from Z decay.

This hypothesis was discussed in several papers [9–14]. We report here on our recent quantitative investigation of the Z-burst scenario, where we have determined the mass of the heaviest Rν as well as the necessary UHECν flux via a maximum likelihood analysis [15].

Our comparison of the Z-burst scenario with the observed UHECR spectrum was done in four steps. First, we determined the probability of Z production as a function of the distance from Earth. Secondly, we exploited collider experiments to derive the energy distribution of the produced protons in the lab system. Thirdly, we considered the propagation of the protons, i. e. we determined their energy losses due to pion and e^+e^- production through scattering on the CMBR and due to their redshift. The last step was the comparison of the predicted and observed spectra and the extraction of the mass of the Rν and the necessary UHECν flux.

II. Z-BURST SPECTRUM

Our prediction of the contribution of protons from Z-bursts to the UHECR spectrum, for degenerate ν masses ($m_\nu \approx m_{\nu_i}$), can be summarized as

$$j(E,m_\nu) = I\cdot F_Z^{-1}\cdot \sum_i \int_0^\infty {\rm d}E_p \int_0^{R_0} {\rm d}r \int_0^\infty {\rm d}\epsilon \qquad (1)$$
$$F_{\nu_i}(E_{\nu_i},r) n_{\nu_i}(r)\sigma(\epsilon)\mathcal{Q}(E_p)\left(-\partial P(r,E_p,E)/\partial E\right),$$

where the total time and angle integrated detector area I and the normalization factor F_Z, which is proportional to the sum of the ν fluxes at centre-of-mass (CM) energy M_Z, are determined later by the comparison with the UHECR data. E is the energy of the protons arriving at Earth. Further important ingredients in our prediction (1) are: the UHECν fluxes $F_{\nu_i}(E_{\nu_i},r)$ at the resonant energy $E_{\nu_i} \approx E_\nu^{\rm res}$ and at distance r to Earth, the number density $n_{\nu_i}(r)$ of the Rνs, the Z production cross section $\sigma(\epsilon)$ at CM energy $\epsilon = \sqrt{2\,m_\nu\,E_{\nu_i}}$, the energy distribution $\mathcal{Q}(E_p)$ of the produced protons with energy E_p, and the probability $P(r,E_p,E)$ that a proton created at a distance r with energy E_p arrives at Earth above the threshold energy E.

The last three building blocks, σ, $\mathcal{Q}$, and P, are very well determined. At LEP and SLC millions of Z bosons were produced and their decays analyzed with extreme high accuracy. We used existing published [16–19] and some improved unpublished [20] data to determine the proton momentum distribution $\mathcal{Q}(E_p)$. Due to the large statistics, the uncertainties of our analysis related to Z decay turned out to be negligible. Similarly, the CMBR is known to a high accuracy. It plays the key role in the determination of the probability $P(r,E_p,E)$ [21,22], which takes into account the fact that protons of extragalactic (EG) origin and energies above $\approx 4\cdot 10^{19}$ eV lose a large fraction of their energies [6,7] due to pion and e^+e^- production through scattering on the CMBR and due to their redshift. $P(r,E_p,E)$, in the form as it has been calculated for a wide range of parameters by two of the present authors [22], was an indispensible tool in our quantitative analysis.

Less accurately known in Eq. (1) are the first two ingredients, the flux of UHECνs, $F_{\nu_i}(E_{\nu_i},r)$, and the neutrino number density $n_{\nu_i}(r)$.

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The former was assumed to have the form $F_{\nu_i}(E_{\nu_i}, r) = F_{\nu_i}(E_{\nu_i}, 0)\,(1+z)^\alpha$, where z is the redshift and where α characterizes the source evolution (see also [3,10]). The flux at Earth, $F_{\nu_i}(E_{\nu_i}, 0)$, has been determined by the fit to the UHECR data. In our analysis we went up to distances R_0 (cf. (1)) corresponding to redshift $z = 2$ (cf. [23]), and uncertainties of the expansion rate [24] were included.

The neutrino number density n_{ν_i} has been treated in the following way. For distances below 100 Mpc we varied the shape of the $n_{\nu_i}(r)$ distribution between the homogeneous case and that of $m_{\rm tot}(r)$, the total mass distribution obtained from peculiar velocity measurements [25]. In this way we took into account that the density distribution of Rνs as hot dark matter (DM) follows the total mass distribution; however, with less clustering. It should be noted that for distances below 100 Mpc the peculiar velocity measurements [25] suggest relative overdensities of at most a factor $2 \div 3$, depending on the grid spacing. We did not follow the unnatural assumption of having a relative overdensity of $10^2 \div 10^4$ in our neighbourhood, as it was assumed in earlier investigations of the Z-burst hypothesis [4,5,9,10,12]. Our quantitative results turned out to be rather insensitive to the variations of the overdensities within the considered range, whose effect is included in our final error bars. For scales larger than 100 Mpc the Rν density was taken according to the big-bang cosmology prediction, $n_{\nu_i} = 56 \cdot (1+z)^3$ cm^{-3}.

III. DETERMINATION OF M_ν AND UHECν FLUX

We compared the predicted spectrum (1) of protons from Z-bursts with the observed UHECR spectrum (cf. Fig. 1). Our analysis included UHECR data of AGASA [26,27], Fly's Eye [28–30], Haverah Park [31,32], and HIRES [33]. Due to normalization difficulties we did not use the Yakutsk [34] results.

The predicted number of UHECR events in a bin was taken as

$$N(i) = \int_{E_i}^{E_{i+1}} \mathrm{d}E \left[A \cdot E^{-\beta} + F_Z \cdot j(E, m_\nu) \right], \qquad (2)$$

where E_i is the lower bound of the $i^{\rm th}$ energy bin. The first term is the usual power-law behavior, which describes the data well for smaller energies [26,27]. For this term we studied two possibilities. In the first case we assumed that the power part is produced in our galaxy. Thus no GZK effect was included for it ("halo"). In the second – in some sense more realistic – case we assumed that the protons come from uniformly distributed, EG sources and suffer from the GZK cutoff ("EG"). In this case the simple power-law-like term is modified, by taking into account the probability $P(r, E_p, E)$, and falls off around $4 \cdot 10^{19}$ eV (see Fig. 1). The second term of the flux in Eq. (2) corresponds to the spectrum of the Z-bursts, Eq. (1). A and F_Z are normalization factors. Note that the following implicit assumptions have been made through the form of Eq. (2): *i)* We have assumed (and later checked) that the UHE photons from Z-bursts can be neglected. *ii)* We have assumed that there are no significant additional primary UHE proton fluxes beyond the extrapolation of the above power-law. This constraint will be relaxed in a future publication [35].

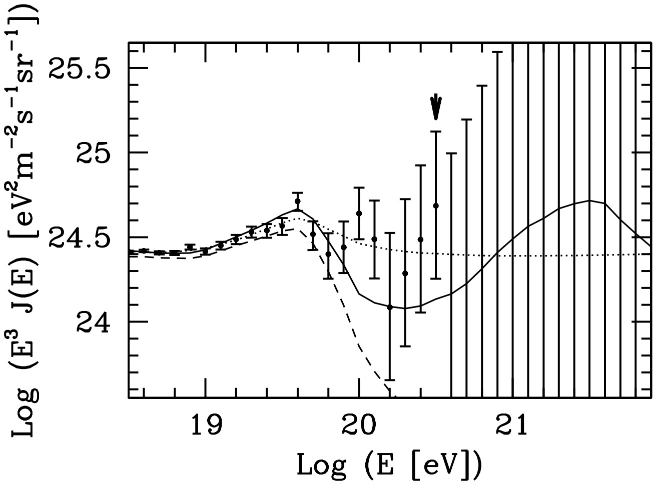

FIG. 1. The available UHECR data with their error bars and the best fits from Z-bursts [15]. Note that there are no events above 3×10^{20} eV (shown by an arrow). Bins with no events show the $1\,\sigma$ upper bounds on the flux. Therefore the experimental value of the integrated flux is in the "hatched" region with 68% confidence level ("hatching" is a set of individual error bars; though most of them are too large to be depicted in full). The dotted line shows the best fit for the "halo"-case. The bump around $4 \cdot 10^{19}$ eV is due to the Z-burst protons, whereas the almost horizontal contribution is the first, power-law-like term of Eq. (2). The solid line shows the "extragalactic"-case. The first bump at $4 \cdot 10^{19}$ eV represents protons produced at high energies and accumulated just above the GZK cutoff due to their energy losses. The bump at $3 \cdot 10^{21}$ eV is a remnant of the Z-burst energy. The dashed line shows the contribution of the power-law-like spectrum with the GZK effect included. The predicted fall-off for this term around $4 \cdot 10^{19}$ eV can be observed.

The expectation value for the number of events in a bin is given by Eq. (2). To determine the most probable value for m_ν we used the maximum likelihood method and minimized [36] the $\chi^2(\beta, A, F_Z, m_\nu)$,

$$\chi^2 = \sum_{i=18.5}^{26.0} 2\left[N(i) - N_{\rm o}(i) + N_{\rm o}(i) \ln\left(N_{\rm o}(i)/N(i)\right)\right], \quad (3)$$

where $N_{\rm o}(i)$ is the total number of observed events in the $i^{\rm th}$ bin. As usual, we divided each logarithmic unit into ten bins. Since the Z-burst scenario results in a quite small flux for lower energies, the "ankle" is used as a lower end for the UHECR spectrum: $\log(E_{\rm min}/{\rm eV}) = 18.5$. Our results are insensitive to the definition of the

upper end (the flux is extremely small there) for which we choose $\log(E_{\max}/\mathrm{eV}) = 26$. The uncertainties of the measured energies are about 30% which is one bin. Using a Monte-Carlo method we included this uncertainty in the final error estimates.

In our fitting procedure we had four parameters: β, A, F_Z and m_ν. The minimum of the $\chi^2(\beta, A, F_Z, m_\nu)$ function is $\chi^2_{\min}$ at $m_{\nu\,\min}$ which is the most probable value for the mass, whereas $\chi^2(\beta', A', F'_Z, m_\nu) \equiv \chi^2_o(m_\nu) = \chi^2_{\min} + 1$ gives the $1\,\sigma$ (68%) confidence interval for m_ν. Here β', A', F'_Z are defined in such a way that the $\chi^2(\beta, A, F_Z, m_\nu)$ function is minimized in β, A and F_Z at fixed m_ν.

Qualitatively, our analysis can be understood in the following way. In the Z-burst scenario a small Rν mass needs large E_ν^{res} in order to produce a Z. Large E_ν^{res} results in a large Lorentz boost, thus large E_p. In this way the *shape* of the detected energy (E) spectrum determines the mass of the Rν. The sum of the necessary UHECν fluxes was then determined from the obtained *normalization* F_Z.

Our best fits to the observed data can be seen in Fig. 1, for evolution parameter $\alpha = 1$. We found a neutrino mass of $2.34^{+1.29(3.74)}_{-0.84(1.66)}$ eV for the "halo"- and $0.26^{+0.20(0.50)}_{-0.14(0.22)}$ eV for the "EG"-case, respectively. The first numbers are the $1\,\sigma$, the numbers in the brackets are the $2\,\sigma$ errors. This gives an absolute lower bound on the mass of the heaviest ν of 0.06 eV at the 95% CL. The fits are rather good; for 21 non-vanishing bins and 4 fitted parameters they can be as low as $\chi^2 = 15.1$. We determined m_ν for a wide range of cosmological source evolution ($\alpha = 0 \div 3$) and Hubble parameter ($H_0 = 0.64 \div 0.78$ km/sec/Mpc) and observed only a moderate dependence on them. The results remain within the above error bars. We performed a Monte-Carlo analysis studying higher statistics. In the near future, Auger [37,38] will provide a ten times higher statistics, which reduces the error bars in the neutrino mass to $\approx$ one third of their present values.

The necessary UHECν flux at E_ν^{res} has been obtained from our fit values of the normalization F_Z. We have summarized them in Fig. 2, together with some existing upper limits and projected sensitivities of present, near future and future observational projects. It is apparent that the flux determination depends much more on the evolution uncertainties than the mass determination. The necessary ν flux appears to be well below present upper limits and is within the expected sensitivity of AMANDA, Auger, and OWL.

IV. COMPARISON WITH $\triangle M_\nu^2$ FROM ν OSCILLATIONS

One of the most attractive patterns for ν masses is similar to the one of the charged leptons or quarks: the masses are hierarchical, thus the mass difference between the families is approximately the mass of the heavier particle. Using the mass difference of the atmospheric ν oscillation for the heaviest mass [24], one obtains values between 0.03 and 0.09 eV. It is an intriguing feature of our result that the smaller one of the predicted masses is compatible on the $\approx 1.3\,\sigma$ level with this scenario.

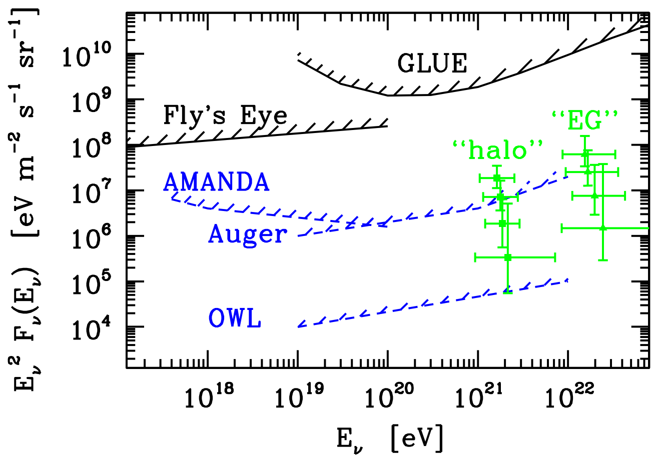

FIG. 2. Differential neutrino fluxes required by the Z-burst hypothesis for the "halo" and the "extragalactic" case [15]. The evolution parameter α takes values 0,1,2,3 from top to bottom for both cases, respectively. The horizontal errors indicate the $1\,\sigma$ uncertainty of the mass determination and the vertical errors include also the uncertainty of the Hubble expansion rate. Also shown are upper limits from Fly's Eye [39] and the Goldstone lunar ultrahigh energy neutrino experiment GLUE [40], as well as projected sensitivities of AMANDA [41], Auger [10,42] and OWL [10,43].

Another popular possibility is to have 4 neutrino types. Two of them – electron and sterile neutrinos – are separated by the solar ν oscillation solution, the other two – muon and tau – by the atmospheric ν oscillation solution, whereas the mass difference between the two groups is of the order of 1 eV. We studied this possibility, too. On our mass scales and resolution the electron and sterile neutrinos are practically degenerate with mass m_1 and the muon and tau neutrinos are also degenerate with mass m_2. The best fit and the $1\,\sigma$ region in the $m_1 - m_2$ plane is shown in Fig. 3 for the "EG"-case. The dependence of this result on the cosmological evolution and on the UHECν spectrum will be discussed elsewhere [35]. Since this two-mass scenario has much less constraints the allowed region for the masses is larger than in the one-mass scenario.

V. DIFFERENCES WITH RESPECT TO YOSHIDA *ET AL.* (1998)

Numerical simulations of Z-burst cascades for $m_\nu \sim 1$ eV, taking into account all known EG propagation effects, were performed by Yoshida *et al.* [10]. Based on

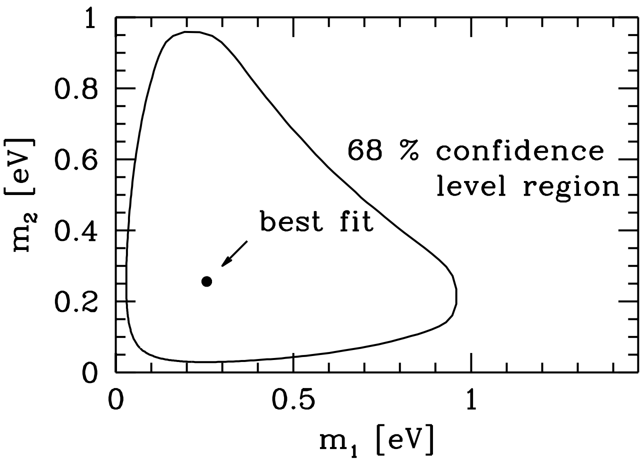

FIG. 3. The best fit and the $1\,\sigma$ (68% confidence level) region in a scenario with two non-degenerate ν masses [15].

case studies, relative overdensities of Rνs ranging from $20 \div 10^3$ on a scale of 5 Mpc were argued to be necessary in order to get a successful description of the UHECR events and rate above the GZK cutoff without violating lower energy photon flux limits and without invoking inconceivable UHECν fluxes. For such large overdensities, most of the UHECRs from Z-bursts originate nearby and their attenuation to the Earth can be neglected. In our case, with realistic overdensities $\leq 2 \div 3$ on scales $\leq$ 100 Mpc, most of the UHECRs from Z-bursts originate from cosmological distances. Therefore, despite of the fact that by construction the overall rate of UHECRs from Z-bursts observed at Earth is the same in both investigations, the predicted spectra are quite different. No large overdensity is needed to reproduce the data. Note that the EG scenario is dominated not by the nearby Z-burst but by the pile-up of Z-burst protons due to the GZK effect (cf. Fig. 1).

VI. CONCLUSIONS

We reported on a comparison of the predicted spectrum of the Z-burst hypothesis with the observed UHECR spectrum [15]. The mass of the heaviest Rν turned out to be $m_\nu = 2.34^{+1.29}_{-0.84}$ eV for halo and $0.26^{+0.20}_{-0.14}$ eV for EG scenarios. The second mass, with a lower bound of 0.06 eV on the 95% CL, is compatible with a hierarchical ν mass scenario with the largest mass suggested by the atmospheric ν oscillation. The above ν masses are in the range which can be explored by future laboratory experiments like the β decay endpoint spectrum and the ν less $\beta\beta$ decay [13,44]. They compare also favourably with the tau(?) neutrino mass range $0.04 \div 4.4$ eV found recently from a detailed analysis of the latest CMBR measurements [45]. We analysed a possible two-mass scenario and gave the corresponding confidence level region. The necessary UHECν flux was found to be consistent with present upper limits and detectable in the near future.

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